Carbon-free Hydrogen and Electricity from Coal: Options for Syngas Cooling in Systems Using a Hydrogen Separation Membrane Reactor

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Outline

1. Schematic overview of the process and connection with previous works

2. Motivations and synergies of Membrane Reactor and Syngas Coolers
   - “Dry” syngas → Syngas coolers → Increase efficiency
   - 2 free parameters: - Hydrogen Recovery Factor (HRF)
- Steam to Carbon ratio (S/C)

3. Construction of the “HRF-S/C space”

4. Movements in this space to obtain different plant configurations (low S/C)

5. Determine final plant configurations

6. Present thermodynamic and economic performances

Coal-to-hydrogen: Schematic process

Syngas Production

O_2 Coal Gasification

Cooling phase

Quench

VS

Syngas Coolers

H_2 Separation

Pressure Swing Adsorbtion

VS

Membrane Reactor

Carbon capture

Physical Solvent

Oxy-fuel

Clean-up
Shift CO→H2

Power Generation
Heat Recovery

Coal-to-hydrogen plants: past works

H_2 Separation

Syngas Cooling

	Pressure Swing Adsorbtion	**Membrane Reactor**
Quench	Lowest Cost	Relatively small increase in efficiency
Syngas Coolers	Slight increase in efficiency Not cost effective	**?**

Same models and assumptions for coherent comparison

Motivations

$$\uparrow H_2O + CO \leftrightarrow CO_2 + H_2 \downarrow$$ Water-gas-shift

CONVENTIONAL:
"WET" syngas required for high H_2 production

PUSH the reaction

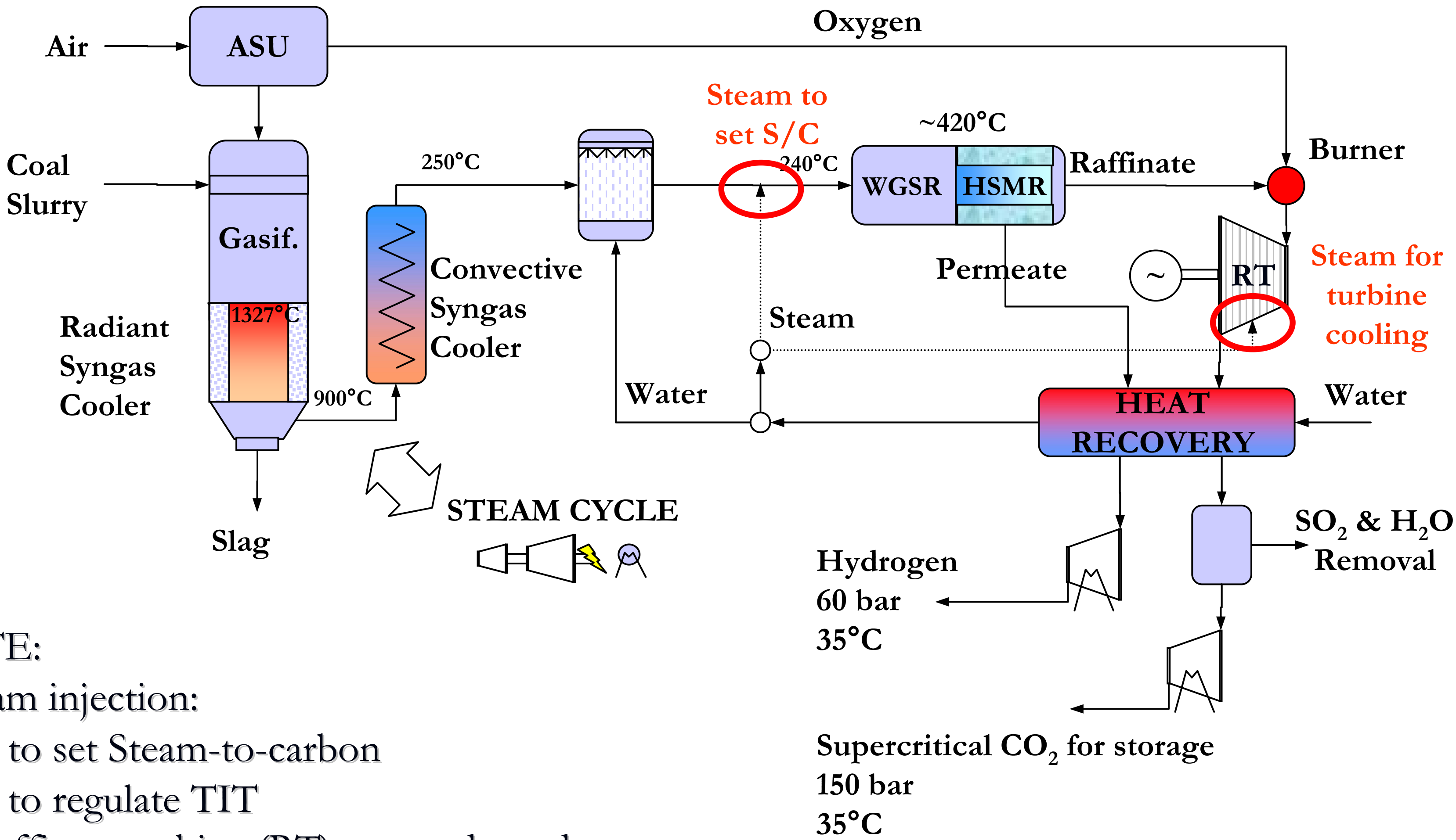
Quench Cooling good match to WGS but relatively inefficient

IDEA:
Relative "DRY" syngas allowed by continuous H_2 permeation

PULL the reaction

Syngas Coolers adoption and potential for improved energy efficiency

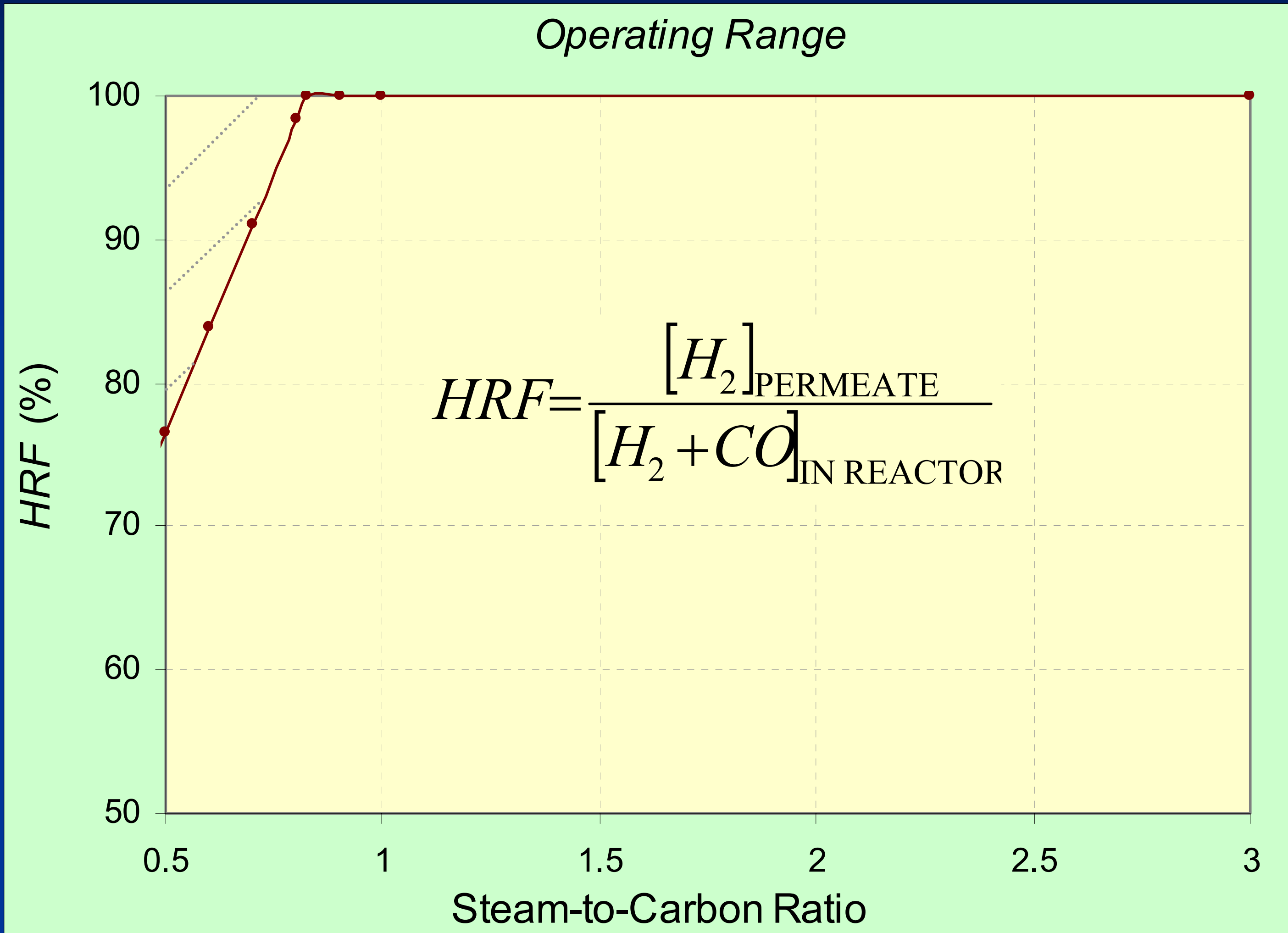
General plant scheme



NOTE:

- Steam injection:
  - → to set Steam-to-carbon
  - → to regulate TIT
- 2 Raffinate turbine (RT) types adopted:
  - → Un-cooled turbine 850°C
  - → Steam blade cooled turbine 1250°C

Constructing (Hydrogen Recovery Factor)-(Steam to Carbon) space



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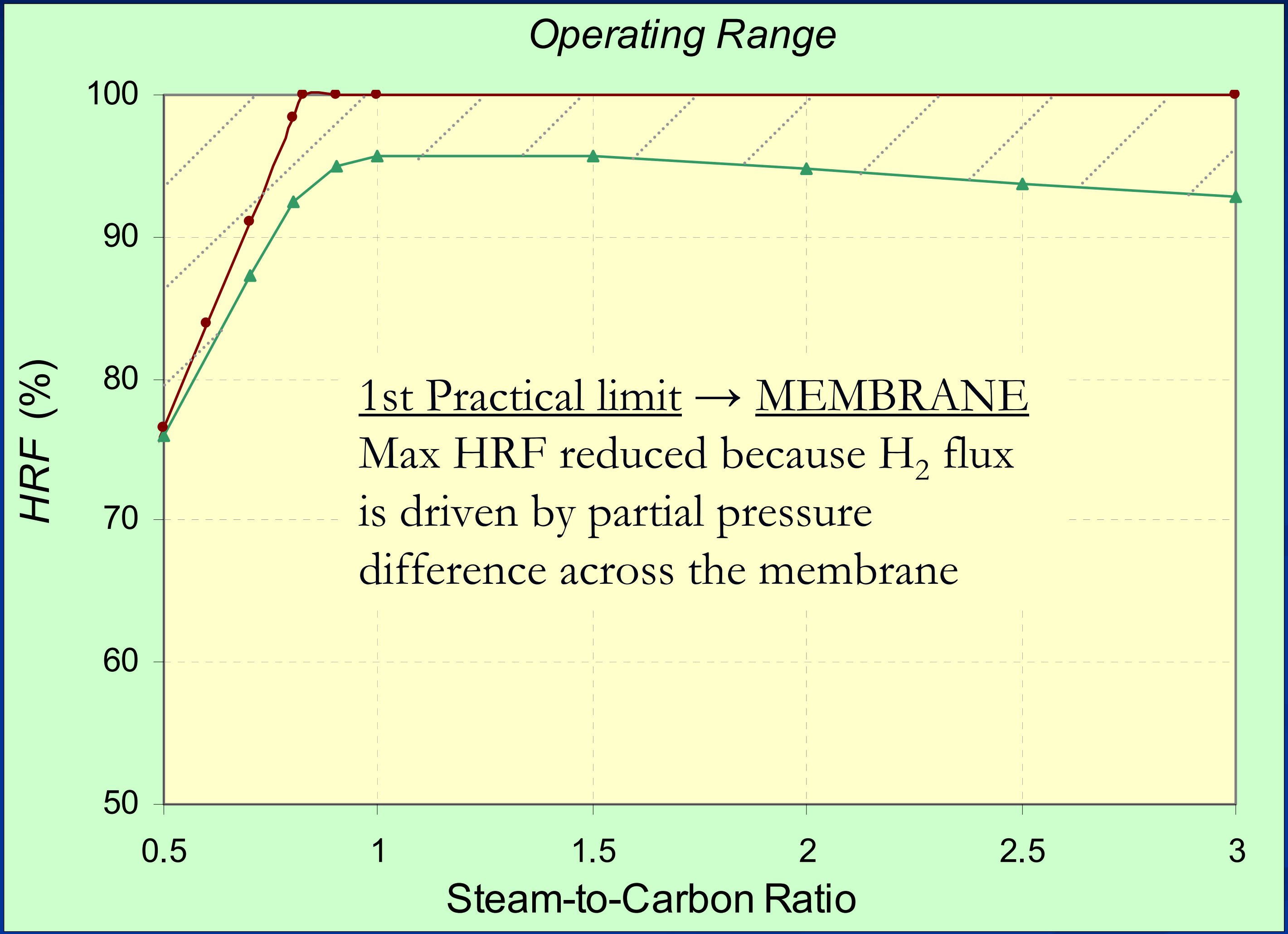

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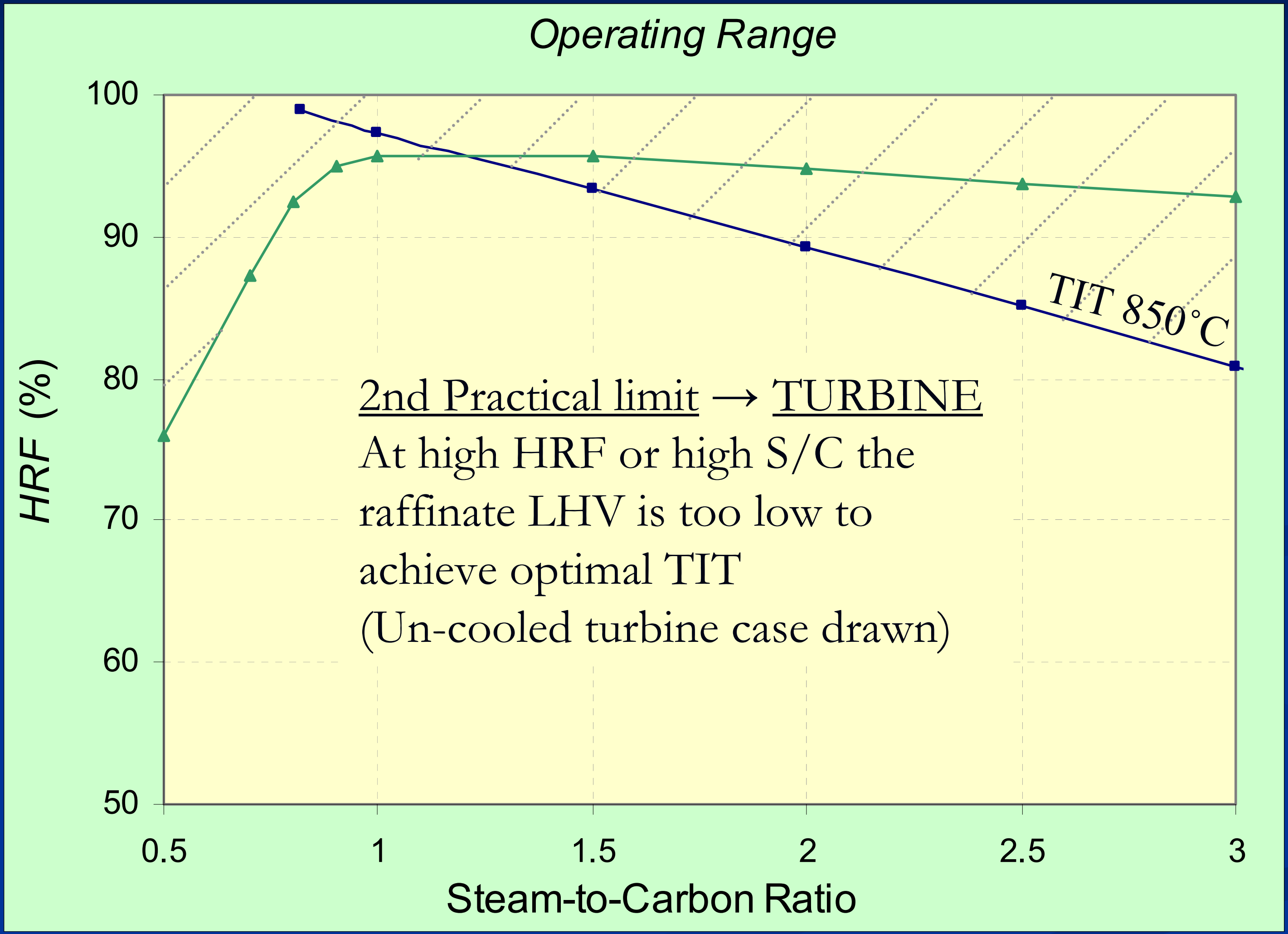
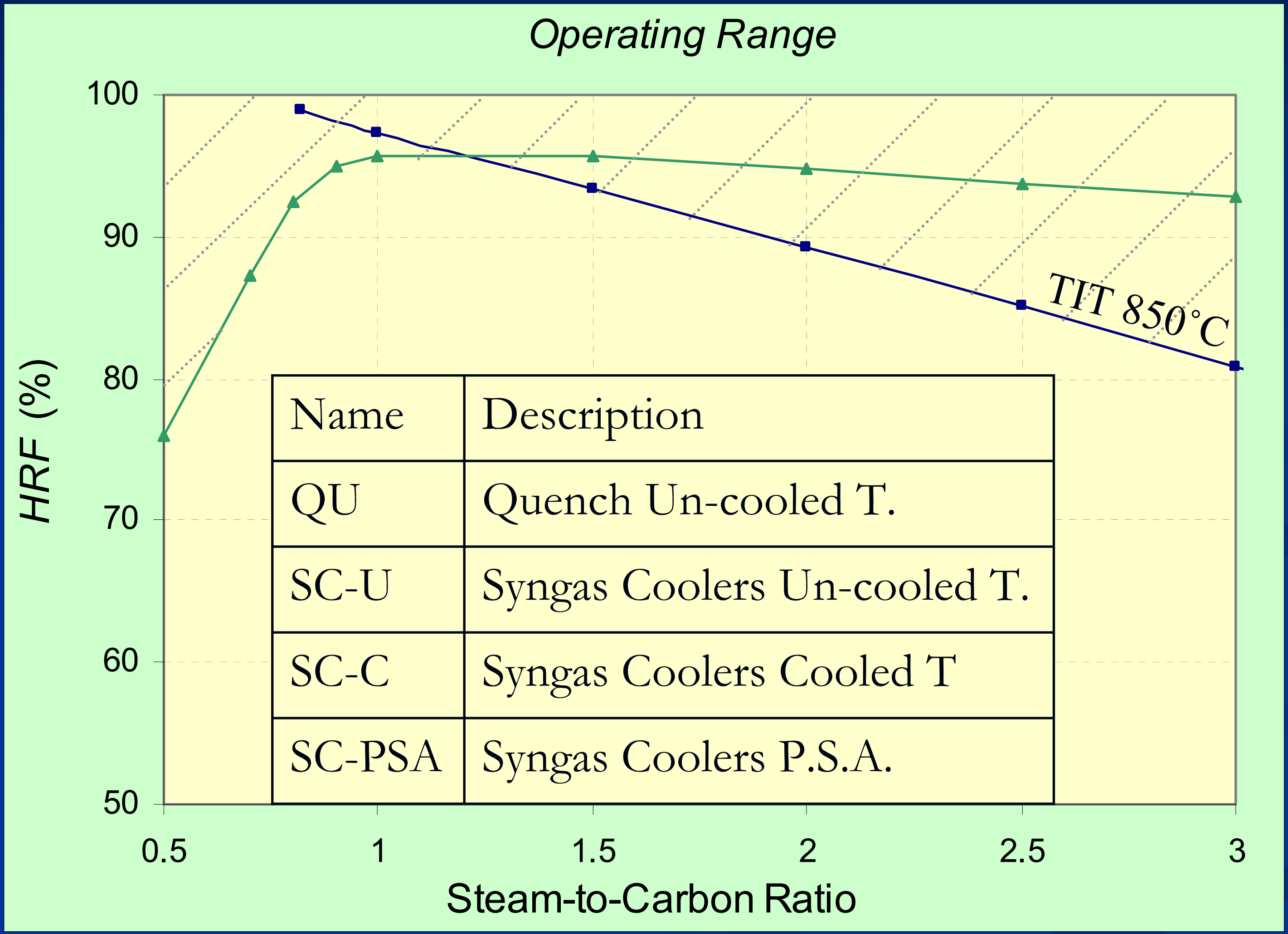
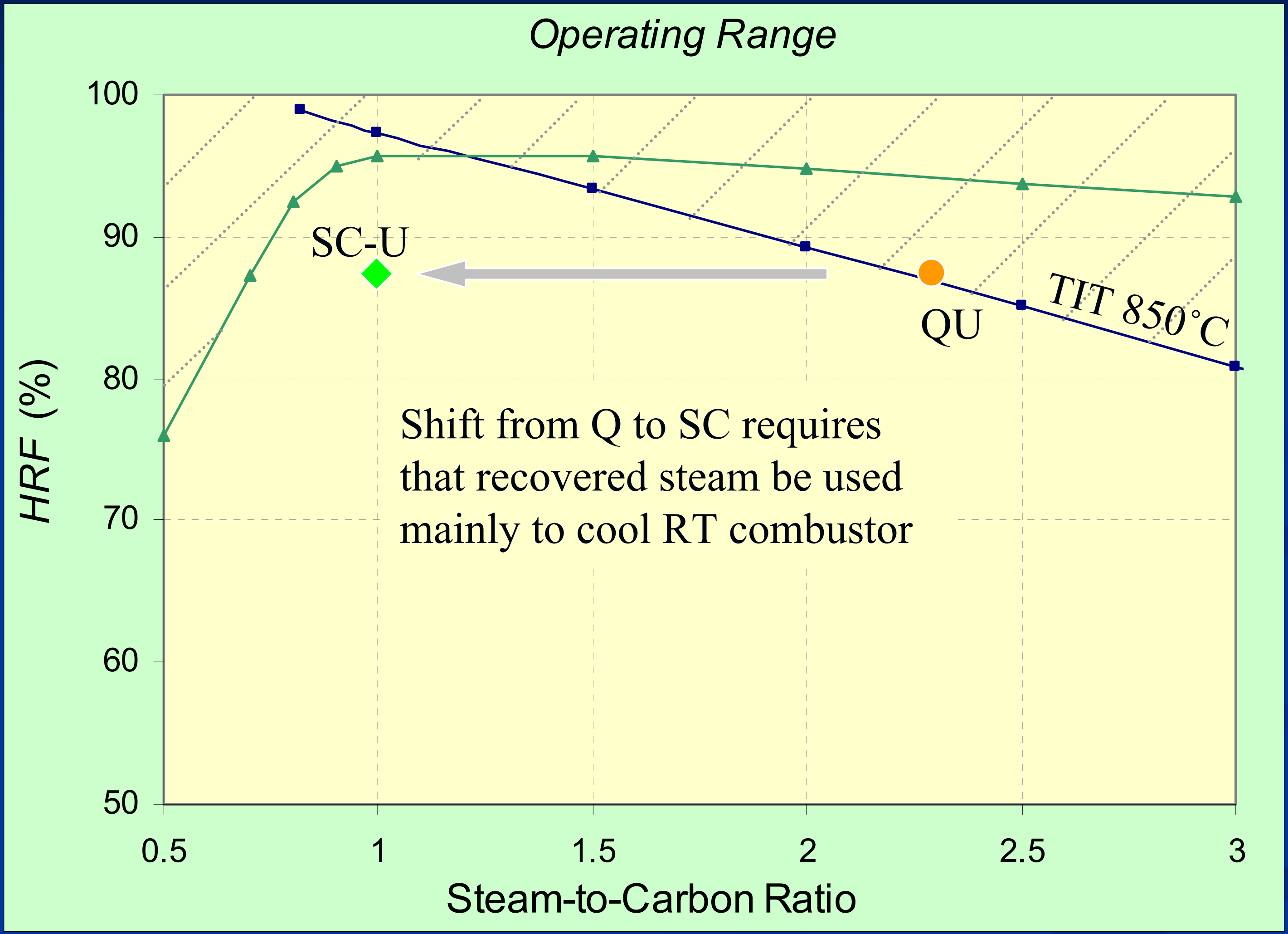


Moving in an (Hydrogen Recovery Factor)-(Steam to Carbon) space

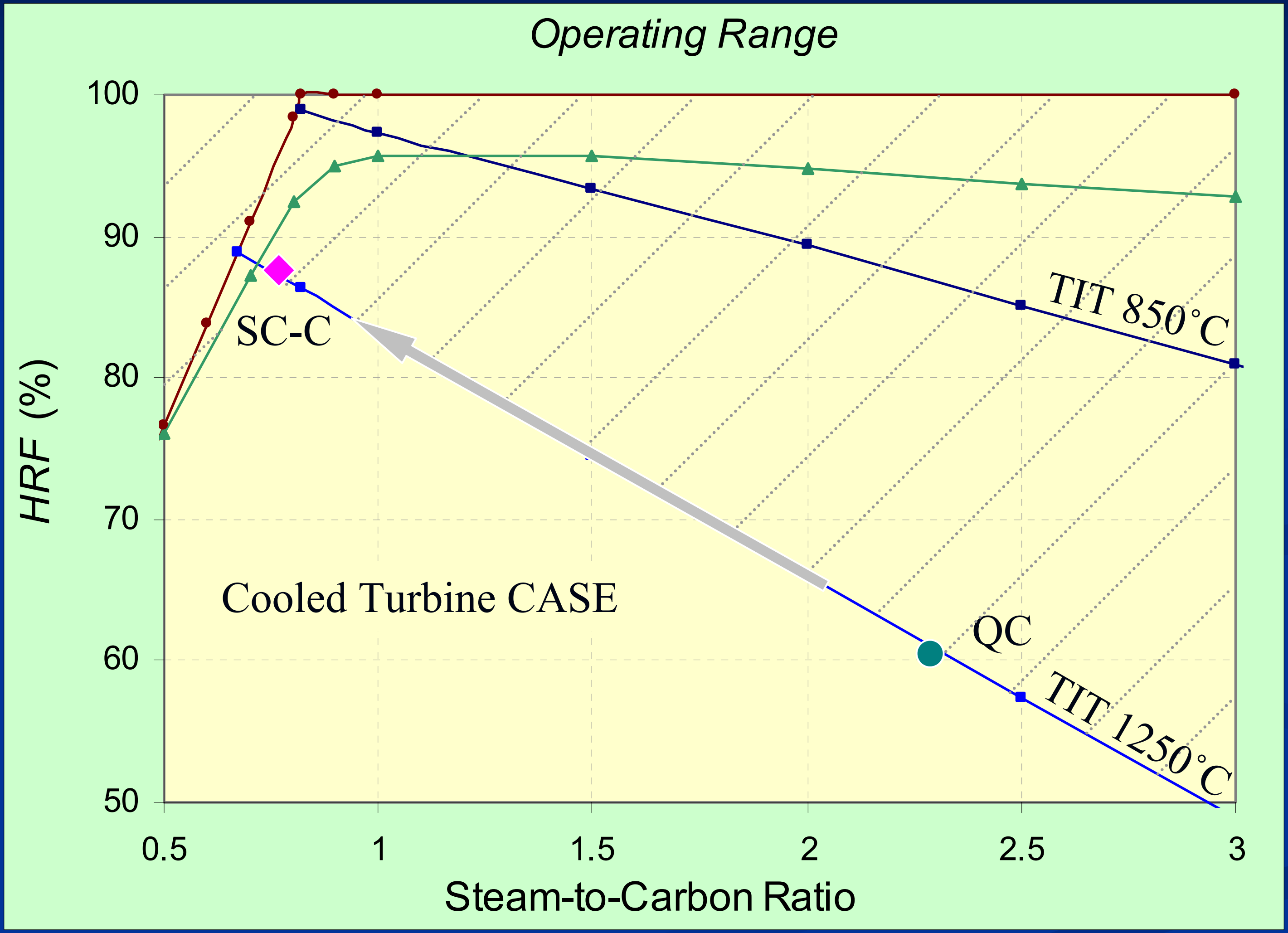


Name	Description
QU	Quench Un-cooled T.
SC-U	Syngas Coolers Un-cooled T.
SC-C	Syngas Coolers Cooled T
SC-PSA	Syngas Coolers P.S.A.

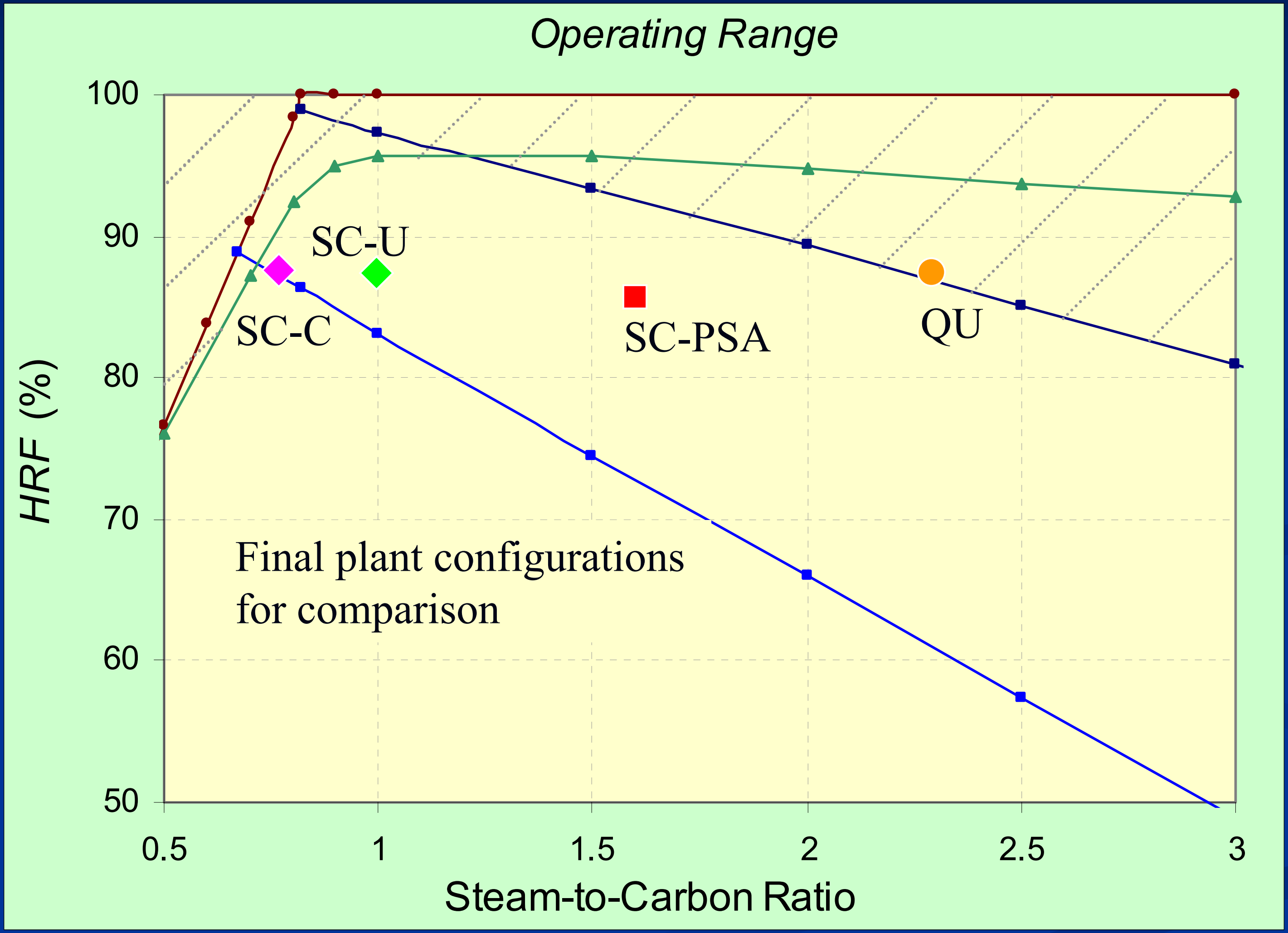
Moving in an (Hydrogen Recovery Factor)-(Steam to Carbon) space



Moving in an (Hydrogen Recovery Factor)-(Steam to Carbon) space



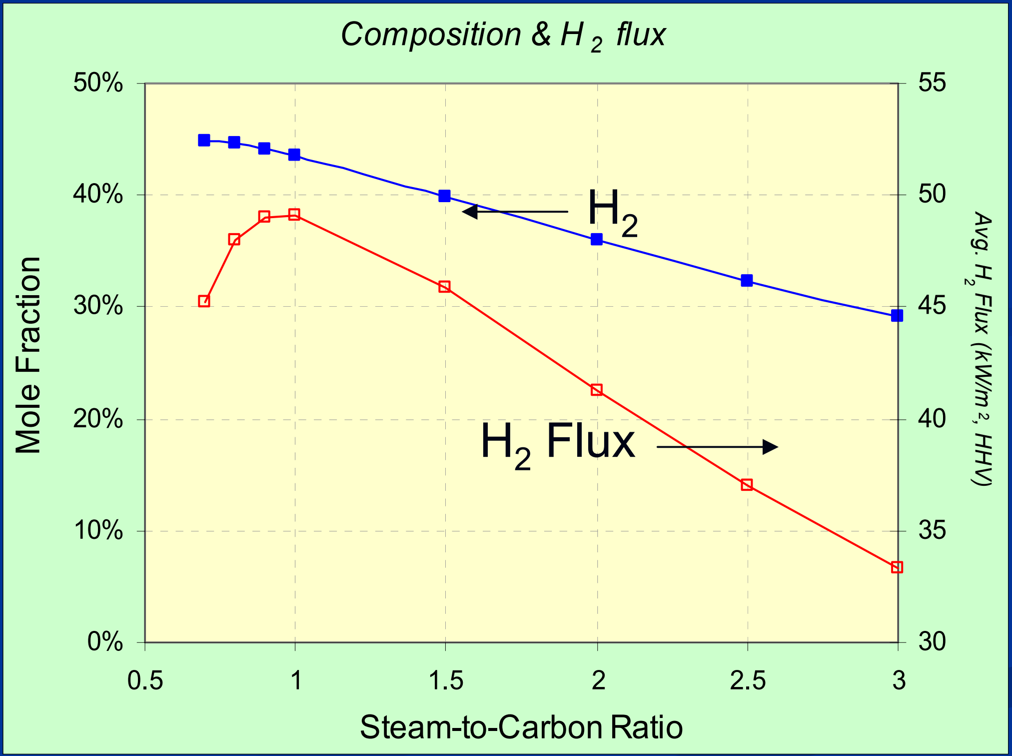
Moving in an (Hydrogen Recovery Factor)-(Steam to Carbon) space



Syngas Coolers & Membrane Reactor Synergies

Higher H_2 permeation flux at lower S/C

- Lower water content (S/C) in the Membrane Reactor increases the hydrogen mole fraction and its partial pressure. Increase in membrane performance (25% with respect to initial quench case)



Results: Plant configurations thermodynamic performance

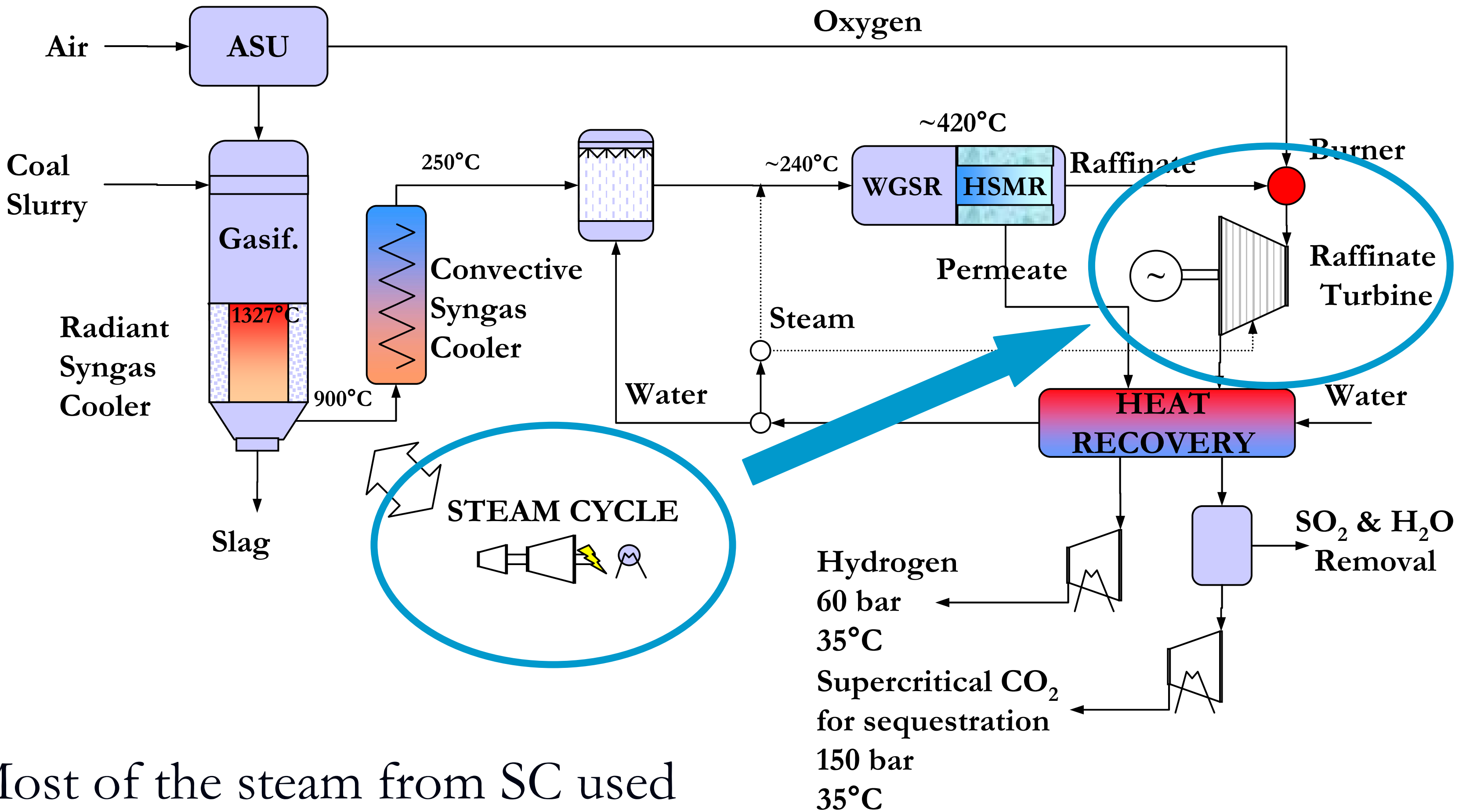
Syngas Cooling Type	Quench	Syngas Coolers
H2 Separation	Membrane	Membrane
Turbine Type	Un-Cooled	Un-Cooled
Steam-to-Carbon	2.38	1
Hydrogen Production (MWth)	1091	1088
Net Power Production (MW)	-11.5	-4.2
Effective Efficiency* (LHV)	59.6%	60%
CO_2 Removal Efficiency	100%	100%

Efficiency increase is NOT as expected…

* Effective system efficiency = LHV H_2 output / LHV (coal input – coal saved**)

** Coal saved based on IGCC with CO2 capture, 36.8% LHV efficiency

This is why…



Most of the steam from SC used in cooling the RT turbine

Results: Plant configurations thermodynamic performance

Syngas Cooling Type	Quench	Syngas Coolers	Syngas Coolers	Syngas Coolers
H2 Separation	Membrane	Membrane	Membrane	PSA
Turbine Type	Un-Cooled	Un-Cooled	Cooled	Cooled
Steam-to-Carbon	2.38	1	0.73	1.52
Hydrogen Production (MWth)	1091	1088	1091	1032
Net Power Production (MW)	-11.5	-4.2	33.4	70.9
Effective Efficiency* (LHV)	59.6%	60%	**63.8%**	**61%**
CO_2 Removal Efficiency	100%	100%	**100%**	**100%**

Syngas Coolers-Membrane reactor-Cooled turbine winning configuration

Results: Plant configurations economic performance

Syngas Cooling Type	Quench	Syngas Coolers	Syngas Coolers	Syngas Coolers
H2 Separation	Membrane	Membrane	Membrane	PSA
Turbine Type	Un-Cooled	Un-Cooled	Cooled	Cooled
Capital* (15% of TCR)	0.59	0.74	0.74	0.76
Carbon Disposal* (at 5$/mt CO_2)	0.089	0.091	0.091	0.13**
CO_2 Removal Efficiency	100%	100%	100%	90.5%
Hydrogen Cost ($/kg)	1.07	1.25	1.18	1.19

* H_2 Cost Components ($/kg H_2)

** CO_2 emission (at 100 $/mt C)

Conclusions

- Membrane reactor characteristic of "pulling" the water gas shift reaction allows the employment of syngas coolers; it is therefore possible to explore low S/C configurations with increased efficiency.

- Membrane performance increases for low water content (S/C~1).

- Un-cooled turbine performance is NOT influenced by S/C variations.

- Cooled turbine is well matched with low water content without requiring low values of HRF. Syngas coolers-Membrane reactor-Cooled turbine configuration has the best thermodynamic performance.

- The economics show that these solutions are slightly not competitive. The increase in performance does not offset the higher capital cost. Key issues: syngas coolers cost & membrane permeability performance.
    - Two stage high pressure gasification
    - Fired tube heat exchanger (cheaper)